Latest Developments of High-Frequency Series Load Resonant Inverter Type Built-In Cooktops for Induction Heated All Metallic Appliances

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***Abstract*- This paper deals with the 1st generation prototype of one-stage boost-half bridge (B-HB) series load resonant (SLR) soft-switching high-frequency (HF) inverter with a lossless snubbing capacitor for a variety of induction heating (IH) appliances. The B-HB SLR HF inverter treated here is based upon a simple dual SLR frequency selection strategy changed automatically in accordance with various metal materials of IH loads. In the first place, the triple SLR frequency (three times of switching frequency) operated B-HB inverter is demonstrated for IH of non-magnetic and low resistivity metallic pans/utensils fabricated by aluminum, copper and multi-layer of aluminum and stainless steel. In the second place, the fundamental resonant frequency (switching frequency) operated B-HB SLR HF inverter for IH is also demonstrated of magnetic and high resistivity metallic pans/utensils fabricated by iron, iron cast and stainless steel. Finally, the principle of operation control, implemental and inherent unique features of the B-HB SLR HF inverter employing automatically dual resonant frequency selection scheme for a variety of IH metallic pans/utensils is described from an experimental point of view, along with its operating performance. This 1st generation HF SLR inverter type built-in IH cooktop with two ranges/three ranges has been put into practice in home energy utilizations in all electricity residential systems.**

Keywords: High frequency resonant inverter, Boost-half bridge topology, Triple series resonant frequency-operated mode, Induction-heated all metallic appliances, Consumer power electronics.

I. INTRODUCTION

In accordance with great advances of power semiconductor devices, sensor devices and microprocessor-based digital controlling devices, as well as passive power circuit components, consumer power electronics have become one major field technology in home energy utilization systems architecture. The electromagnetic-induction eddy current based electric heating or induction heating (IH) processing system technology employing high-frequency (HF) inverters and cycloconverters have attracted special interest for consumer induction heating applications.

The HF resonant inverter type built-in IH cooktops composed of PFC rectifier, HF inverter, planar type working coil, crystal spacer. Direct heating of pans/utensils by the HF resonant inverter type built-in IH cooktops have some inherent remarkable advantageous points of high efficiency, easy cleaning, rapid cooking, comfortable environment, safety, high reliability and easy power management.

In recent years the HF inverter type IH appliances, IH rice cooker and warmer, IH cooktop, IH hot water producer and IH super-heated steamer have developed so far for home energy applications from an energy saving point of view. The IH cooktop family with two/three ranges which incorporates HF resonant soft switching inverters as active-clamp, half bridge and full bridge circuit topologies has rapidly become more popular in Japan and Europe.

However, most of HF inverter type built-in IH cooktop equipments could not heat effectively the metallic pans/utensils fabricated by non-magnetic and low resistivity metallic materials such as aluminum, copper and aluminum - stainless steel multi-layer, on the basis of eddy current based IH principle.

The authors have developed a novel prototype of cost-effective built-in IH cooktop family incorporating boost-half bridge (B-HB) HF series load resonant (SLR) inverter with optimum resonant-frequency changing scheme, which is practically applicable for all metallic pans/utensils fabricated by low resistivity metallic materials to high resistivity ones and put into practice as commercial market.

This paper presents the triple resonant frequency-operated B-HB series resonant inverter using the latest IGBT with anti-parallel FRD is demonstrated and designed, which can operate at a small damped oscillating current mode with three times of switching frequency under a condition of SLR soft commutate for the IH aluminum, copper metal pans/utensils. The operating principle, control and operating performances of B-HB SLR inverter are described and discussed from an experimental point of view.

II. PRINCIPLE OF INDUCTION HEATING AND REQUIREMENTS FOR IH ALL METALLIC OBJECTS

In induction heating process, a HF magnetic field can be generated by passing a HF electric current from a HF inverter

with a frequency of several tens of kHz into a planar working coil positioned below the pans/utensils, which act as the IH loads of the HF inverter. The electromagnetic induced eddy currents are generated in the bottom of the pans/utensils in proportional to the high-frequency magnetic fluxes caused on the basis of electromagnetic induction principle. As a result, eddy current-based Joule heat is generated by equivalent value to the product of the metallic pans/utensils electrical resistance and square of the eddy current. The pan/utensil themselves then heats up in the principle as shown in Fig. 1.

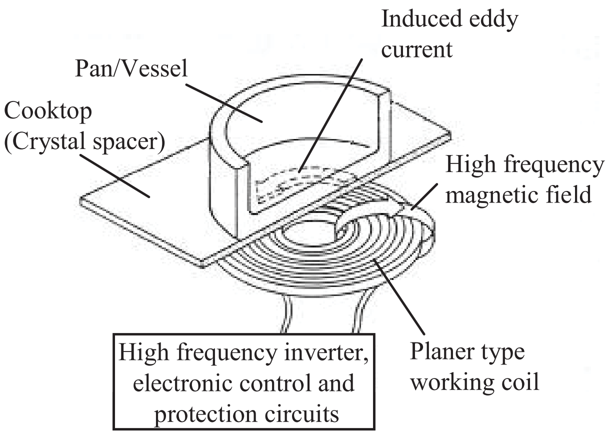

Fig. 1. Operating principle of HF induction heating.

In addition, in induction heating process, heating power P can be approximately expressed by,

$$P = R_s \cdot I_e^{\,2} \propto \sqrt{\rho \cdot \mu \cdot f} \cdot (N \cdot I_L)^2 \tag{1}$$

where R_s : skin effect resistance, I_e : eddy current through the working coil with the metallic pan/utensil , ρ : resistivity of the pan/utensil, μ : permeability of the objects, f : frequency of the working coil current, N : number of litz wire windings of the working coil and I_L : working coil current under objects. The heating power P is proportional to R_s and the square of I_e. The skin effect resistance R_s is proportional to $\sqrt{\rho \cdot \mu \cdot f}$ and I_e is proportional to the intensity of magnetic field H, i.e., N and I_L.

Especially, because the aluminum material is non-magnetic substance, μ (=1, $\mu=\mu_0=4\pi \text{x} 10^{-7}$) of aluminum is much smaller than those of magnetic substances such as iron or stainless steel. Besides, ρ of aluminum is much smaller than that of iron or non-magnetic stainless steel. For example, as indicated in Table 1, the product of ρ and μ in case of aluminum is 1/25 that of non-magnetic stainless steel. If the same induction heating power of aluminum pan as that of non-magnetic stainless steel pan is delivered to the load, then $\sqrt{f} \cdot (N \cdot I_L)^2$ must be kept to be 5.

In this IH appliance development, f of HF current to IH loads is designed approximately as three times of that of the conventional, N is increased up to approximately 1.7 times that conventionally used, if I_L is almost designed so as to be the same value. Although the switching power loss can be increased as f is higher. In order to reduce the increased switching power losses, the triple resonant frequency operated HF resonant inverter under the condition of one third switching frequency is considered.

III. Triple Resonant Frequency Operated High Frequency Inverter

A. Circuit Description

The circuit configuration of the small damped resonant oscillating inverter with triple resonant frequency is shown in Fig.2. This triple resonant frequency operated HF inverter is developed for IH cooktops applicable for all metallic pans/utensils.

The main power conversion circuit mainly consists of boost-half bridge resonant inverter, high boost smoothing capacitor DC link, a passive PFC rectifier.

TABLE I
PHYSICAL PARAMETERS OF VARIOUS MATERIALS FOR IH COOKTOP

Material / Physical value	Iron	Non-magnetic stainless steel	Aluminum	Copper
Resistivity ρ ($\mu\Omega$m)	0.17	0.7	0.027	0.017
Relative permeability μ_s	200	1	1	1
Conventional IH cooktop	○	○	×	×
Newly developed IH cooktop	○	○	○	○

Remark; ○ applicable × Not applicable

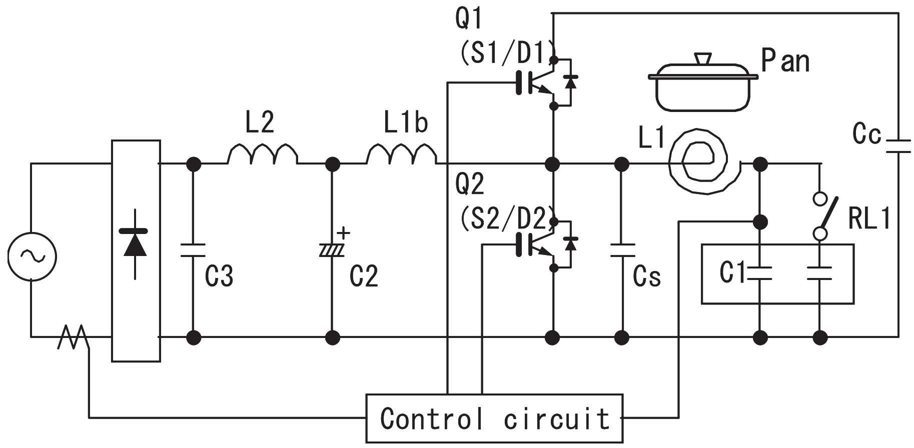

Fig. 2. Total circuit of the newly developed HF resonant inverter for IH cooktops applied for all metallic pans/vessels.

A B-HB HF resonant inverter with SLR circuit consists of working coil L1 and resonant capacitor C1, the power semiconductor switching devices Q1(S1/D1) and Q2(S2/D2). The relay RL1 is used to change the series resonant capacitor C1 according to the material of the pan/utensil. Boost converter in one stage B-HB HF inverter consists of boost choke coil L1b, S2, D1 and high-voltage DC smoothing capacitor Cc. HF inverter and boost converter have common switch S2 of Q2. For soft-switching, lossless snubbing capacitor Cs changeable by an undescribed switching device is connected to Q2 in parallel.

Moreover, especially when light weight objects of non-magnetic materials such as aluminum pans/utensils are heated directly, a Lorenz force acts on heated pans/utensils by the HF magnetic field and the eddy current induced in the pans/utensils. Since variations of HF inverter supply voltage lead to the change of a Lorenz force and mechanical oscillation of pan-vibration sound, smoothing capacitor C2 of output side in passive PFC rectifier, which consists of electrolytic capacitor bank, and boost smoothing film capacitor Cc perform sufficient voltage-smoothing.

B. Operation Principle for Low-resistivity Non-magnetic Objects

Let's consider the circuit operation in case that the materials as aluminum and copper of pans are low-resistivity and non-magnetic. The relay RL1 keeps open in this state. The circuit parameters and design specifications of B-HB HF inverter become as shown in Table 2. Figures 3 and 4 give the explanation of the circuit operation principle of the newly-developed B-HB HF resonant inverter using IGBTs. This circuit includes four operating modes during one switching period as shown in Fig.4. The steady-state operation of triple resonant frequency-operated HF SLR inverter is described below by its relevant voltage and current waveforms.

■ ***Mode 1***; (Q1:Off, Q2:On)

In mode 1, two loops in the circuit are composed of loop (1) and loop (2).

In loop (1): C2 – L1b – Q2 – C2; the magnetic energy is stored into the boost inductor L1b.

And then in loop (2): C1 – L1 – Q2 – C1; the energy stored in the resonant capacitor C1 is delivered to the pan with working coil. C1 is discharged resonantly.

■ ***Mode 2***; (Q1:Off, Q2:On)

In mode 2, two loops in the circuit are composed of loop (1) described above and loop (3).

In loop (3): C1 – D2 – L1 – C1; the energy stored in C1 is delivered to the pan. C1 is charged resonantly.

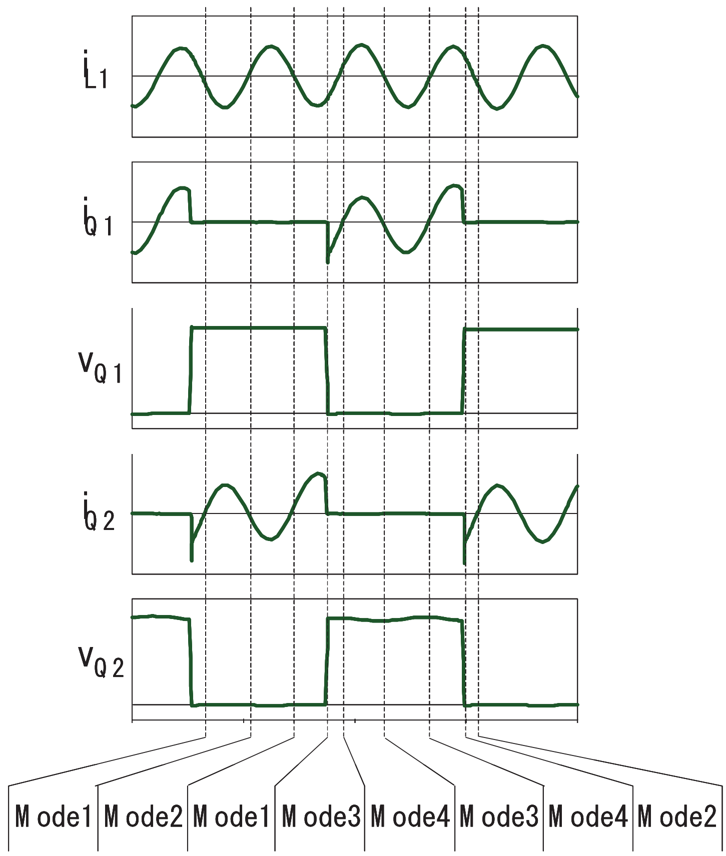

Fig. 3. Relevant voltage and current waveforms of the newly developed HF resonant inverter when low-resistivity non-magnetic materials pans; aluminum/copper are heated.

■ ***Mode 3***; (Q1:On, Q2:Off)

In mode 3, two loops in the circuit are composed of loop (4) and loop (5).

In loop (4): C1 – L1 – D1 – Cc – C1; the energy stored into Cc is delivered to the pan. C1 is discharged resonantly.

In loop (5): C2 – L1b – D1 – Cc – C2; the magnetic energy stored into the boost inductor L1b is released by charging Cc via D1.

■ ***Mode 4***; (Q1:On, Q2:Off)

In mode 4, two loops in the circuit are composed of loop (5) described above and loop (6).

In loop (6): C1 – Cc – S1 – L1 – C1; the energy is delivered to the pan. C1 is charged resonantly through S1 of Q1.

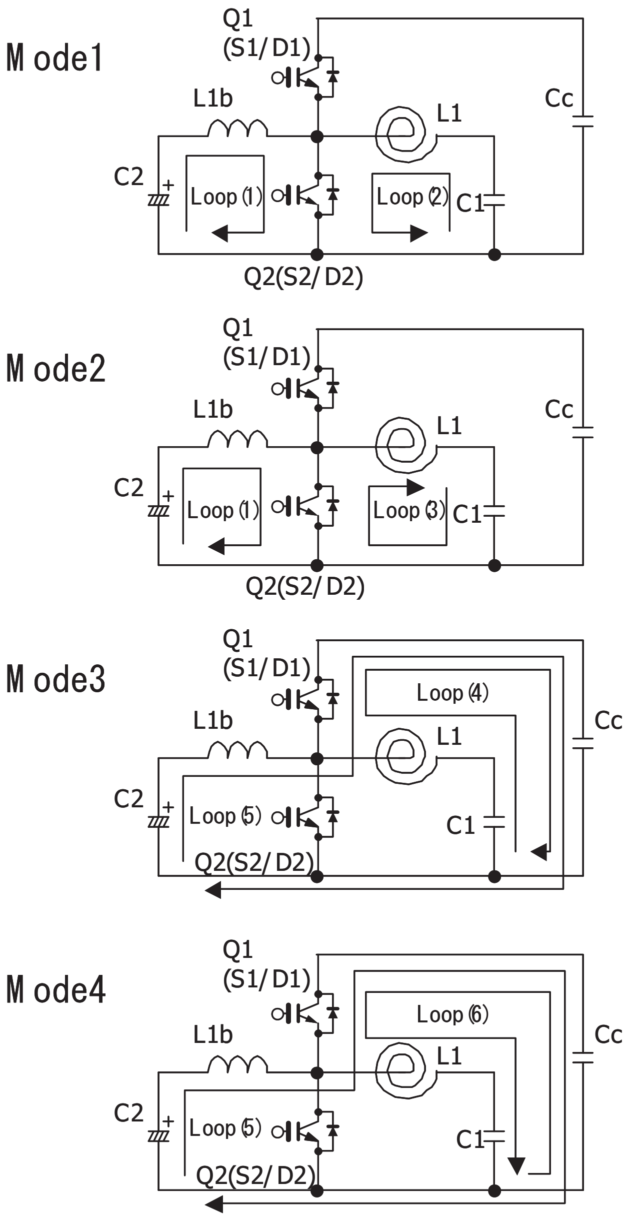

Fig. 4. Operating mode transitions and switching mode equivalent circuit of newly developed HF resonant inverter for IH low-resistivity non-magnetic materials pans.

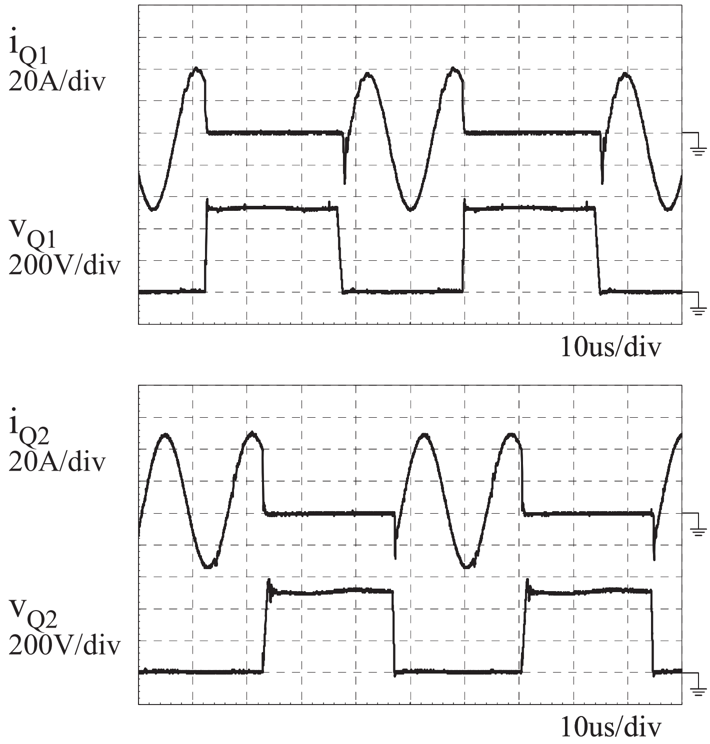

Fig. 5. Measured voltage and current operating waveforms for Q1(S1/D1) and Q2(S2/D2) when an aluminum pan/utensil in 2kW is heated by IH principle.

TABLE II
CIRCUIT PARAMETERS OF THE NEWLY DEVELOPED HIGH FREQUENCY INVERTER

Working Coil with metal pan	L1	with Aluminum Pan (at 60kHz)	227	μH
			1.8	Ω
		with Iron Pan (at 23kHz)	312	μH
			9.2	Ω
Charge-up Inductor	L1b	280		μH
DC Inductor	L2	2 (x 2pcs)		mH
Series Resonant Capacitor	C1	with Aluminum Pan	0.03	μF
		with Iron Pan	0.24	μF
DC Capacitor	C2	470 (x 3pcs)		μF
Charge-up Capacitor	Cc	10		μF
Lossless Snubbing Capacitor	Cs	0.05 / 0.01 (changeable)		μF

Remarks: fr:Resonant Frequency 60kHz
fo:Switching Frequency (Output Frequency) 20kHz

This circuit repeats the operating switching mode in order of mode 1, mode 2, mode 1, mode 3, mode 4, mode 3, mode 4, mode 2, and mode 1 as shown in Fig. 3. The resonant frequency equal to natural frequency of L1 and C1 is designed so as to be about three times of the switching frequency (inverter output voltage frequency) of Q1 and Q2. Since the pan is non-magnetic and low-resistivity material, the resonant current with a small damping factor does not attenuate in the period of each Q1 and Q2 turning on. Figure 5 shows measured operating voltage and current waveforms of Q1 and Q2. As mentioned above, the switching frequency of Q1 and Q2 is set to be approximately 20kHz, so the resonant frequency of the oscillating current passing through L1 and C1 is estimated as approximately 60kHz.

So, this circuit manages both output of HF magnetic field corresponding to HF oscillating current which is suitable for IH of aluminum pans/utensils and reduction of the switching losses of Q1 and Q2 by lowering the switching frequency of Q1 and Q2. Heating effective power dissipated in IH load is controlled by varying switching frequency and minute change of duty ratio around 0.5 of Q1 and Q2.

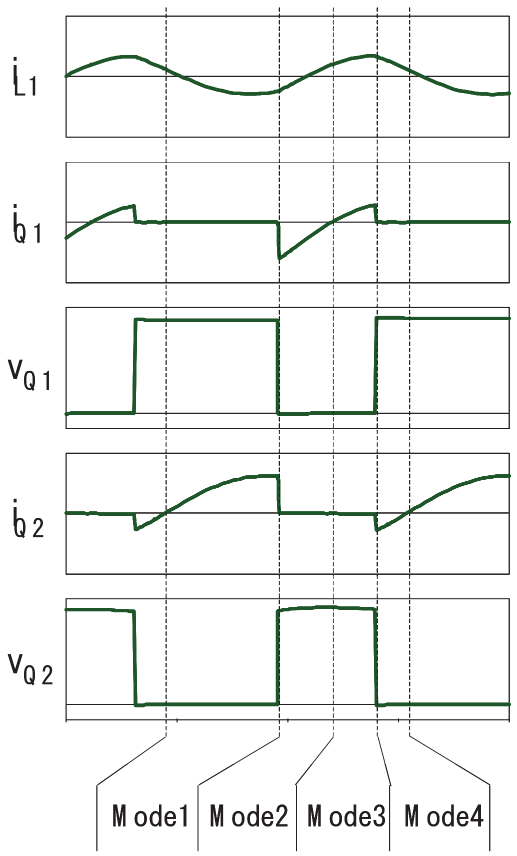

Fig. 6. Operating waveforms of newly developed HF resonant inverter when the pan is heated for high-resistivity materials; the iron and stainless steel.

C. *Operation Principle for Pans of High-resistivity Magnetic Materials*

Next, let's describe the circuit operation in case that the material of pan is high-resistivity and magnetic materials such as iron, iron cast and stainless- steel. In this case, the relay RL1 turns on to close and the circuit parameters become as indicated in Table 2. Figures 6 and 7 give the explanation of the circuit operation principle. Each switching operation mode for heating the iron pans/utensils is almost the same as the switching equivalent circuits for heating the aluminum pans/utensils but mode transition order.

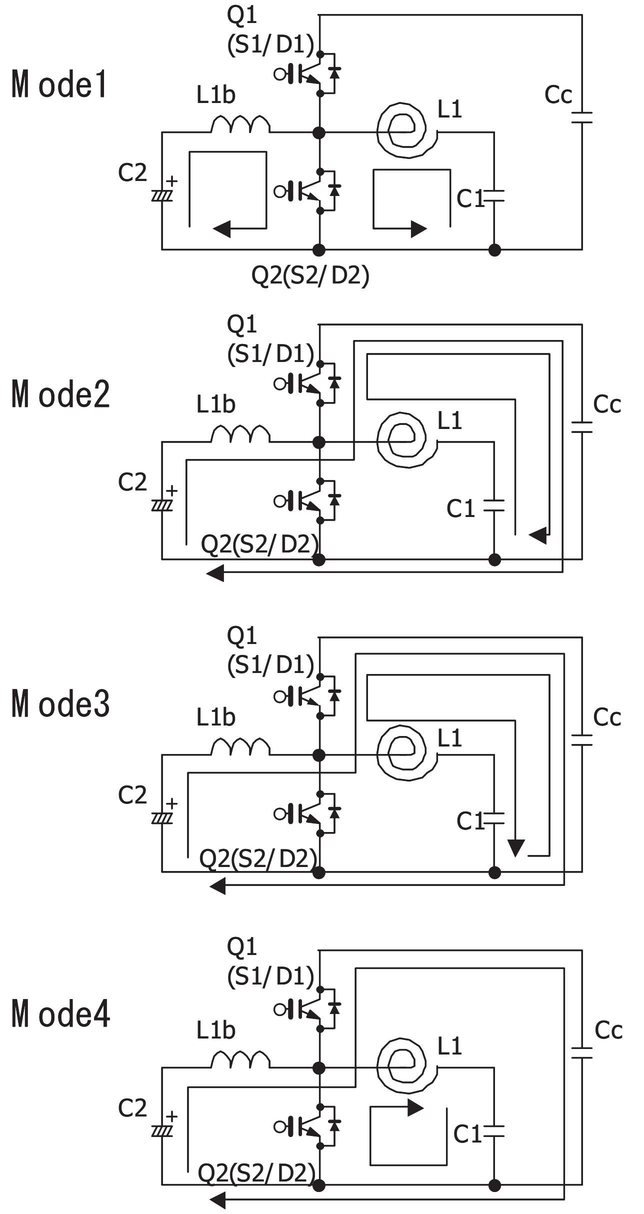

Fig. 7. Operating mode transitions and switching mode equivalent circuit of newly developed HF resonant inverter when the pan is heated for high-resistivity materials; the iron and stainless steel.

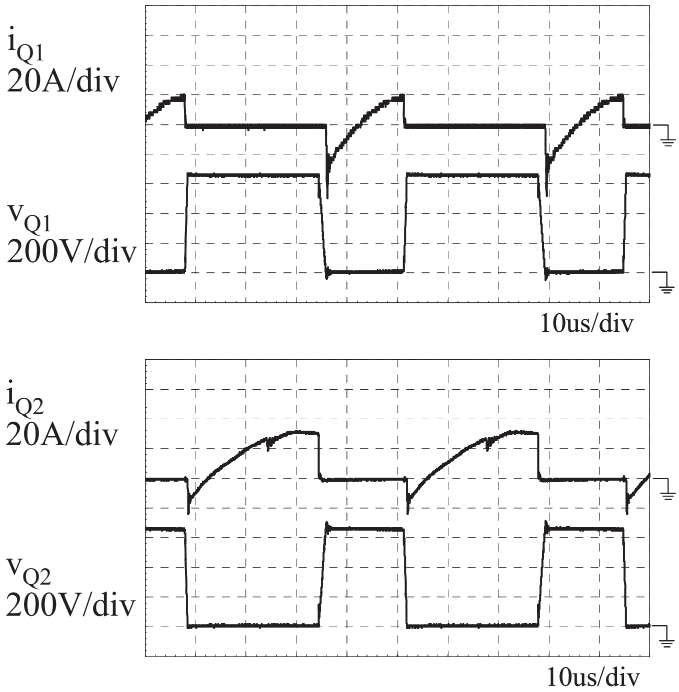

Fig. 8. Measured relevant voltage and current operating waveforms for Q1(S1/D1) and Q2(S2/D2) when an iron pan/stainless steel pan is heated in 2kW output.

In this case, this B-HB HF circuit performs repeating its operating mode in order of mode 1, mode 2, mode 3, mode 4, and mode 1 as shown in Figs. 6 and 7. The resonant frequency of L1 and C1 is designed so as to be approximately equal to the switching frequency of Q1 and Q2.

To heat aluminum pans/utensils with lower coil current, the number of litz wire windings of L1 is designed so as to be 42, approximately 1.7 times as compared with that conventionally used. So, it is required for induction heating of pans with high-resistivity materials, such as iron and stainless steel, to apply high voltage to the B-HB inverter to achieve enough coil current. In this B-HB HF inverter circuit, that is easy because voltage across Cc is boosted by operation of L1b, S2, and D1. Figure 8 shows measured operating voltage and current waveforms of Q1 and Q2. The conduction time of Q2 is longer than that of Q1. The voltage of boost operation depends on conduction time of Q2, so that, as the conduction time is longer, voltage across Cc tends to be higher. Figure 8 indicates that voltage across Cc is charged up to about 650V. Heating power is controlled by varying duty ratio of Q1 and Q2 with a constant switching frequency of 23kHz.

IV. OPERATING PERFORMANCES

A. High Frequency Inverter Implementation

Figure 9 shows the interior appearance of PC boards of the newly-developed B-HB SLR HF inverter type for IH cooktops designed for all metallic pans/utensils. This circuit mainly consists of two PC boards. Switching devices of B-HB SLR HF inverter and control circuit are assembled on the same first PC board. Large size power devices such as resonant capacitors, smoothing capacitors and relay interface are constructed on the second PC board. Moreover, heavy weight inductor with magnetic cores such as a boost choke inductor with powder core and a passive filter inductor with laminated Si-steel core are fixed on the holder supported by springs. The dimension of PC board size including heavy weight inductor holder is about 23cm in width x 23cm in depth x 4.5cm in height x 2pcs.

The 4th generation trench gate IGBTs (60A/950V) produced by Toshiba Semiconductor Co., Ltd as Q1 and Q2 in HF resonant inverter are incorporated.

Figure 10 shows the appearance of the specially-designed working coil for induction heated all metallic objects. Figure 11 shows the enlarged photograph of the litz wire for the working coil. To reduce the HF resistance of the working coil, the litz wire consists of 1,620 entwined 50μm diameter insulated copper wires.

B. Operating Characteristics

a) Power Regulation

Figure 12 illustrates the input power vs. the switching frequency of Q1 and Q2 characteristics when an aluminum pans/utensils are heated with the pulse frequency modulation methods of the triple resonant frequency (three times as switching frequency) operated mode. The small change of the switching frequency realizes wide power regulation.

Figure 13 illustrates the input power vs. the duty ratio of Q2 characteristics when an iron pans/utensils are heated with the pulse width modulation methods of the fundamental resonant frequency (equal to switching frequency) operated mode. The more the duty ratio of Q2 becomes large, the higher the charge-up capacitor Cc voltage is boosted up, so the input power goes up.

b) Zero Voltage Soft Switching Operation

Figure 14 illustrates the observed switching voltage and current waveforms of Q1 and Q2 when aluminum pan is heated. Fig. 14 shows the enlarged switching voltage and current waveforms when Q1 and Q2 turn off, respectively.

As can be seen in Fig. 14, the switch voltage waveform is going up with a slow slope by the charging effect of the lossless snubbing capacitor Cs. Moreover, this B-HB SLR inverter circuit works with the switching frequency of about 20kHz in different from the resonant frequency of about 60kHz in this case. As a result, turn-off transition power dissipation in Q1 and Q2 is dramatically decreased.

The turn-off transition power dissipations in newly-developed B-HB SLR HF inverter are estimated as 12W for Q1 and 19W for Q2 respectively, which are calculated from the actual waveforms.

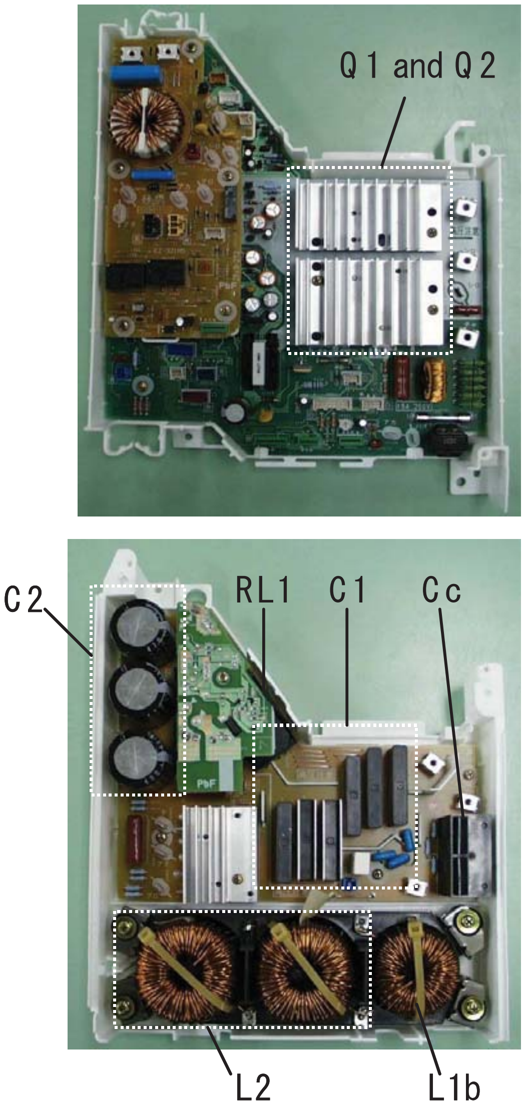

Fig. 9. Photographs of the PC boards of the newly developed HF resonant inverter type cooktops for IH all metallic pans/utensils.

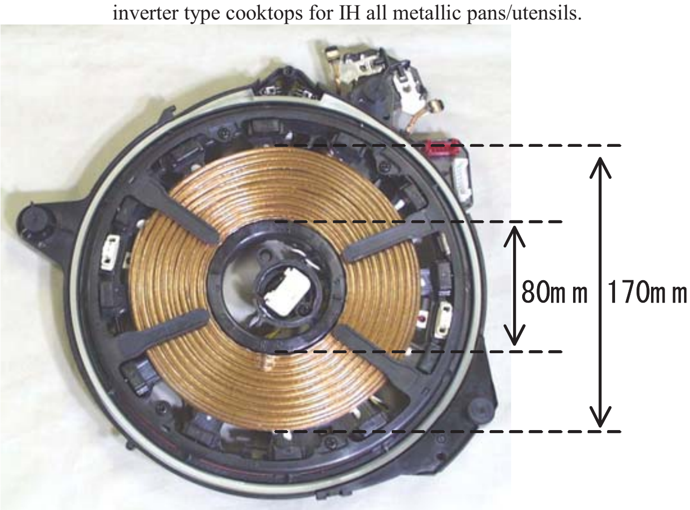

Fig. 10. Exterior appearance of the working coil incorporated into the newly developed HF resonant inverter type cooktops for IH all metallic type pan/utensil.

Fig. 11. Enlarged appearance of the litz wire for the working coil incorporated into the newly developed HF resonant inverter type cooktops for IH all metallic type pan/utensil.

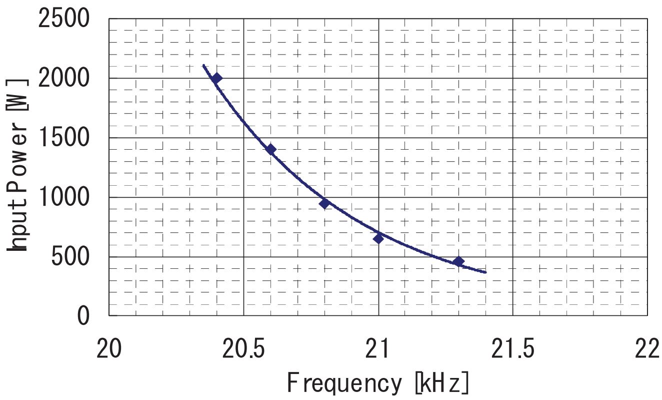

Fig. 12. Input characteristics of the newly developed HF resonant inverter when aluminum pans/utensils are heated.

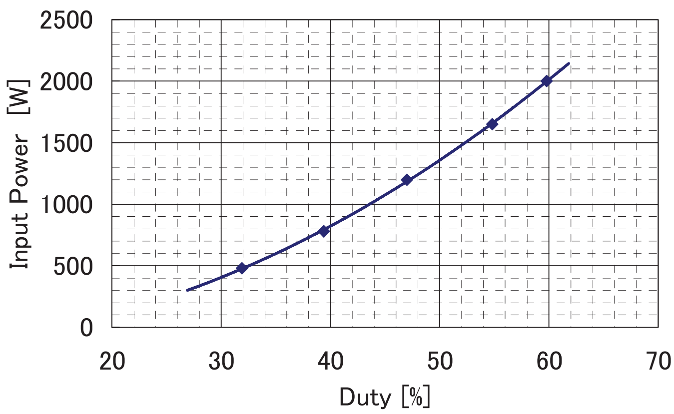

Fig. 13. Input characteristics of the newly developed HF resonant inverter when iron pans/utensils are heated.

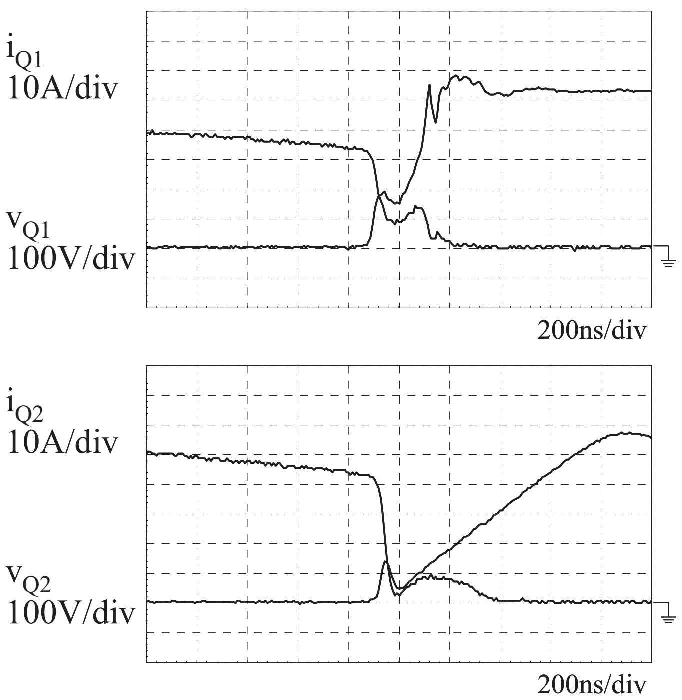

Fig. 14. Measured switching voltage and current waveforms for Q1(S1/D1) and Q2(S2/D2) when an aluminum pans/utensils in 2kW is heated by IH principle.

Fig. 15. Whole appearance of the newly developed HF resonant inverter type cooktop for IH all metallic pans/utensils.

TABLE III
GENERAL DESIGN SPECIFICATIONS OF NEWLY DEVELOPED HIGH FREQUENCY RESONANT INVERTER TYPE IH COOKTOP

Power Supply	Single phase 200V_{rms} AC (50Hz/60Hz)	
Rating Power	4.8kW	
	Left IH Heater (Conventional)	3kW (Except for low-resistivity non-magnetic pans/vessels)
	Right IH Heater (Newly developed)	2kW (For all-metallic pans/vessels)
Dimension	60cm (W) x 56cm (D) x 23cm (H)	
Weight	23kg	

V. CONCLUSIONS

In this paper, conceptual series load resonant high frequency inverter with optimum dual mode resonant capacitor selecting scheme has been developed for consumer IH appliances, which includes one stage packed boost-half bridge soft switching pulse modulation inversion circuit with the intermediate high boost DC link, and simple front-end PFC rectifier. The operating principle, specific control and pulse modulation methods of the triple resonant frequency (three times as switching frequency) operated high frequency resonant inverter and the fundamental resonant frequency (equal to switching frequency) operated one were described and confirmed respectively from an experimental point of view, together with its operating performances.

The 1st generation cost-effective products of aforementioned series resonant high frequency inverter type built-in all metal IH cooktops family with two/three ranges has been demonstrated firstly in the world, which is applicable for not only low resistively metallic materials such as aluminum and copper but also high resistivity metallic materials such as iron and stainless-steel.

In the future, the advanced generation all metal IH appliances which incorporate into the high frequency resonant inverter and its related active PFC rectifier should be proceeded with the aid of (i) further the improvement of power semiconductor devices; Super-Junction MOSFETs, SiC/GaN MOSFETs, and IGBT with SiC-SBD, (ii) cost-effective circuit topologies and control schemes; magnetic integration, multi-phase/interleaving, time-sharing principle, (iii) optimum design of working coil fabricated by litz wire assemble, toward further improved requirements on high efficiency, high power density, and high performances.

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